ANALYSIS

22(70), August 1, 2014

ISSN 2278–5469 EISSN 2278–5450

Discovery

Evaluation of the Destruction Procedure of Eccentric Braced Frames against Progressive Collapse using APM method

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Publication History
Received: 28 May 2014
Accepted: 07 July 2014
Published: 1 August 2014

Citation
Seyyed Abdonnabi Razavi, Seyyed Afshin Mohebi. Evaluation of the Destruction Procedure of Eccentric Braced Frames against Progressive Collapse using APM method. *Discovery*, 2014, 22(70), 7-13

ABSTRACT
Based on most design codes, buildings are designed to bear regular loads including dead and live gravity loads, winds, earthquakes, etc. And their efficient lifetime is determined accordingly. Due to unnatural and unpredicted factors such as fire, accidents and explosion, the load which influences the structure is much greater than the design loads. Therefore because of this accidental imposed damage and a probable elimination of the adjacent structures elements, the diffusion process of the destruction may be greatly hazardous. This event could be so dangerous that can disturb the static balance of the structure. In this article a twelve stories structure with an eccentric braced frame is modeled in accordance with Iran's design codes and is analyzed by an unlinear dynamic analysis since the sudden elimination of the elements is a dynamic phenomenon and this is done in order to achieve a resistant design against a progressive collapse. Utilizing alternative load path scenario (APM) which is introduced in DOD2009 guideline, the critical columns and their related braced frames was eliminated from the numerical model to analyze the force response of the structure in the adjacent members and the resistance of the structure in different situations and to evaluate the capability of this structure to holdback this deficiency. Results indicate more displacement in corner columns than the middle columns. Furthermore, elimination of the columns that are located in the upper floors has result in a further displacement in the connecting nodes comparing to lower floors.

Keywords—Progressive, Collapse, Dynamic Analysis, APM, Alternative Path method.

1. INTRODUCTION

Progressive collapse is a chain-like destruction of structural elements that is created as a result of thrusting abnormal loads to the structure. However, this destruction may happen locally, But a huge destruction might happen due to the final damages. A progressive collapse might happen as a result of different reasons such as mal-design, mal-construction, or not taking the proportion of loads and the structure condition into account. Also, abnormal phenomena such as unnatural loads like vehicle impacts with structural elements, bomb explosion, or gas explosion could cause progressive collapse.

Although the advent of progressive collapse phenomenon to the field of structure engineering is not that old, three important events drew the engineers' attention. The first event was demolishing Ronan Point building in 1968. The second event was destruction of Murrah Federal building in 1995, and the third event was an airplane explosion and crashing into the World Trade Center buildings in September 11th, 2001 following which the northern and southern towers were annihilated. The causes of the progressive collapse in the three buildings are different; the similarity though, lies in the elimination of an element following a chain process as a result of the primary destruction of an element [4]. The Marine Barracks terrorist suicidal attacks in 1983, Khobar towers in Saudi Arabia in 1996, and U.S embassies in Kenya and Tanzania in 1998 are other examples of the elimination of a column caused by abnormal loads [1].

In most codes, design is conducted based on normal loads, such as dead or live loads, snow, wind, or earthquake. Indeed, the loads less likely to happen are not considered. While, in high level structures such as vital city structures, densely crowded structures, hospitals, power plants, and generally all the structures in the field of service providing should be resistant to such a phenomenon. In the past years, different codes and standards have looked into this subject. Nonetheless, most of them have failed to provide practical and feasible solutions for designing structures resistant to the progressive collapse. Recently, the General Service Administration (GSA) has issued a guideline known as GSA2003 [2] to design of Federal Department buildings resistant to the progressive collapse, and also department of defence (DoD) introduced a guideline known as UFC - DoD2009 [3], which has been welcomed by the engineers.

There are two direct design methods in UFC: the enhanced local resistance method and the alternate path method. The enhanced local resistance method aims to harden critical structural members (e.g., perimeter columns, wall sections) to offer satisfactory strength and ductility to resist progressive collapse. In comparison, using the alternate path method, a designer must ensure that the building is able to bridge over selected load-bearing elements that are notionally removed, one at a time, from the original intact building to simulate their sudden loss when subjected to damaging extreme loads [5].

Based on this method, scenarios are defined according to which columns are eliminated under different conditions. Under these conditions, the structure reaction to the fault in the system is analysed. Since eliminating the column and its repercussions are accidental and sudden, redistribution of the forces in the members also happens quickly. That's why; the destruction procedure entails dynamic analysis. However, in some articles the column elimination has been done one time period [8, 9, and 10]. Nevertheless, Powell et al. studying different methods of analysis concluded that the amplification factor of 2 in the linear static analysis can render satisfactory results [6]. Also, in the two guidelines of GSA2003, and Unified Facilities Criteria (UFC) - DoD, the dynamic amplification factor have been suggested for multiplying by the load combination [7].

In this article, a 12 stories structure with an eccentric braced frame is modeled in accordance with Iran's design codes and is analyzed by an unlinear dynamic analysis since the sudden elimination of the elements is a dynamic phenomenon and this is done in order to achieve a resistant design against a progressive collapse. Utilizing alternative load path scenario (APM) which is introduced in DOD2009 guideline, the critical columns and their related braced frames was eliminated from the numerical model to analyze the force response of the structure in the adjacent members and the resistance of the structure in different situations and to evaluate the capability of this structure to holdback this deficiency.

2. ANALYSIS PROCEDURE

To investigate the progressive collapse based on Iran's national codes of construction, eccentric braced steel frames are designed in different cases and the obtained results are compared. The obtained results from the force responses of the spots and point displacements as a result of elimination of columns in different levels are the criteria for the effect of the progressive destruction phenomenon in the intended structures. Therefore, a 12 stories structure with eccentric braced steel frame according to the Iranian code for design of steel structures [11] and considering the Standard No.2800 [12] – Iranian Code of Practice for Seismic Resistant design of Building - was modeled and designed. Having calculated the beams, columns, and braces sections, the structure, using a dynamic

analysis, was studied based on the column elimination in different cases with APM method response to the existent fault in the structure. To design against the progressive collapse, U.S. General Services Administration GSA [2] and UFC [3] guidelines were used. The dynamic amplification factor was considered 2 based on the intended guidelines.

3. MODELING AND LOADING

A. Modeling

In eccentric braced frames, braces are designed to remain resilient in a way the energy scattering with resilient form changes in the intended areas yields a cutting connection [13].

In this study a 12 stories structure was designed using current sections of ST37 steel with the yielding tension of F_y=2400 kg/cm^2 and ultimate tension of F_u=3700 kg/cm^2 with a braced steel frame. The intended model has 7 panels of 5 meters on X axis and also 7 panels of 5 meters on the Y axis. The height of the stories is taken 3 meters. Based on this, considering no opening on the floor, the occupancy area of each floor is 1225 square meters. The column plan type of the structure is available in Figure1.

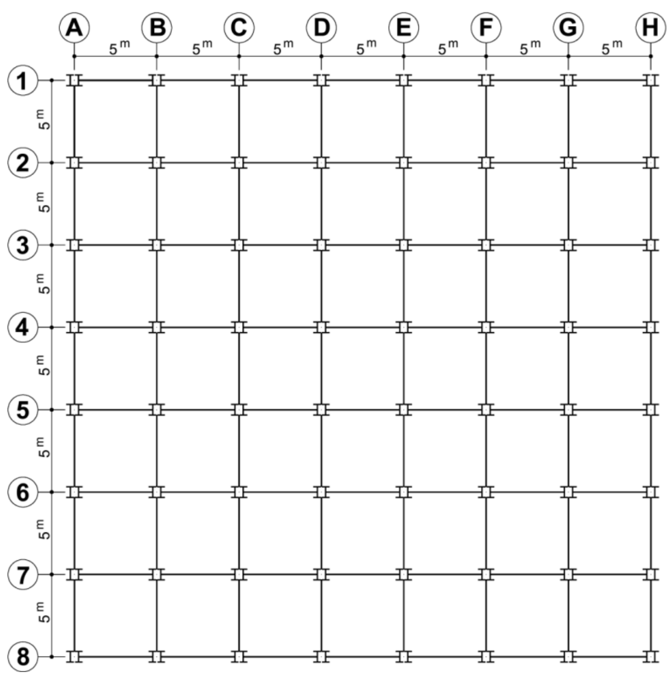

Figure 1 Column type plan for the studied structure

For columns, the double of IPE, for the beams the IPE, and for braces, UNP profiles have been used. If need be, beam and columns are strengthened using plates. Since the system conditions are considered similarly in both X and Y directions, the distance to the centers of the columns is considered in a way that when the gyration radiuses are equal on the two axes, the angularity values on X and Y axes become equal too and subsequently the direction of the column is not of importance. Recommended font sizes are shown in Table 1.

B. Loading

The gravitational loads on the structure are distinguished as surface dead loads of 500 kg/m^2 and surface live load of 300 kg/m^2. Also, the load of surrounding walls is applied 700 kg/m locally. Moreover, a diaphragm as equal to all the stories considering the fatality of 0.05 has been allocated. According to the UFC-DoD instructions for calculating special static amplification factor 2 has been multiplied just as the Equation1 by the load combination.

$$2(DL+0.25LL+WALL) \qquad (1)$$

Where DL, is the uniformed surface dead load of the stories with inner partitions based on kg/m2, LL is the uniformed surface live load of the stories based on kg/m2, and WALL is the distributed dead linear load of surrounding walls based on kg/m. The applied surface loads are transferred once they have been multiplied by the tributary width by the panels on the beams automatically. Figure2 shows the being analyzed building section after applying the loads.

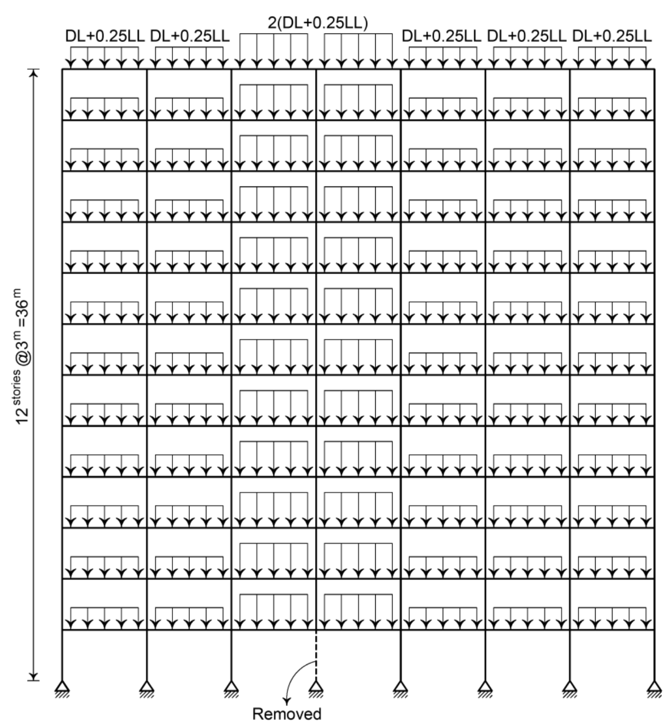

Figure 2 Applying loads in a static analysis to study the progressive collapse potential

4. DYNAMIC ANALYSIS OF COLUMN ELIMINATION

For considering the dynamic analysis, column was eliminated based on expectable cases in the instructions, and was replaced by the reaction of the axis force. Since the column elimination

phenomenon is a dynamic phenomenon by nature, the applied loads on the frame were analyzed as illustrated in Figure3.

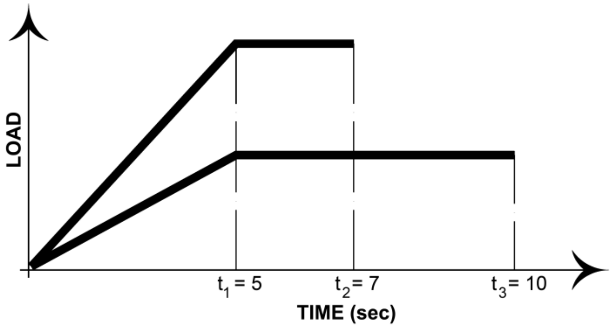

Figure 3 Applying loads in a dynamic analysis to study the progressive collapse

In the software analysis, applying loads were considered in a way as to consider the abruptness of column elimination. To this end, for simulating this effect, loads were applied as Figure 4 shows for the structure to be in balance from 0 to t_1 and the member force be removed in t_2 suddenly to simulate the effect of the column elimination and study the dynamic effects.

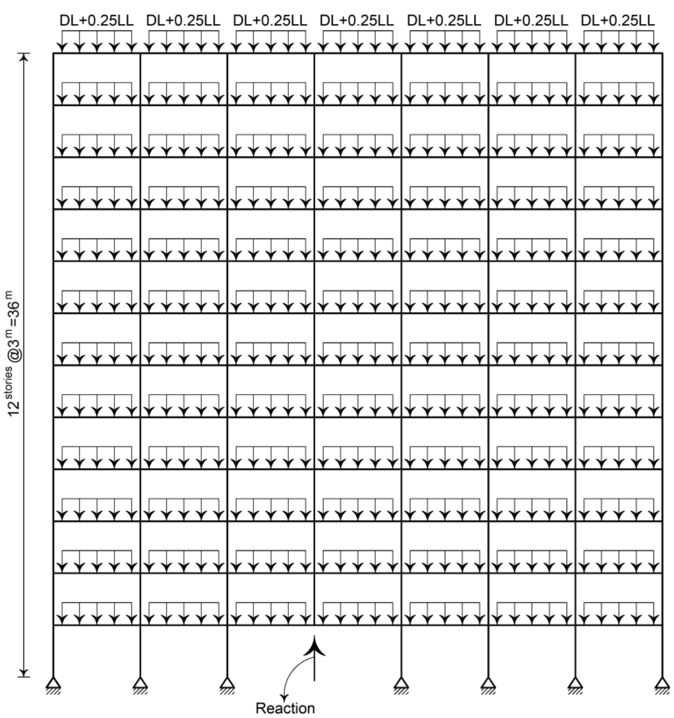

Figure 5 Analyzing the time history of the applied loads in a dynamic analysis

5. THE COLUMN ELIMINATION CASES

Table I includes 9 different recommended positions stated by DoD that is for the structure under study. In positions were the eliminated column abuts braces, both column and braces are eliminated simultaneously and the results are analyzed accordingly. Besides, schematic progressive collapse procedures for cases 1 to 9 shown in Figure5.

TABLE I. THE COLUMN ELIMINATION CASES

Case	Eliminated Column	Floor
1	Corner column	1^{st} floor
2		6^{th} floor
3		12^{th} floor
4	Middle column	1^{st} floor
5		6^{th} floor
6		12^{th} floor
7	Side column	1^{st} floor
8		6^{th} floor
9		12^{th} floor

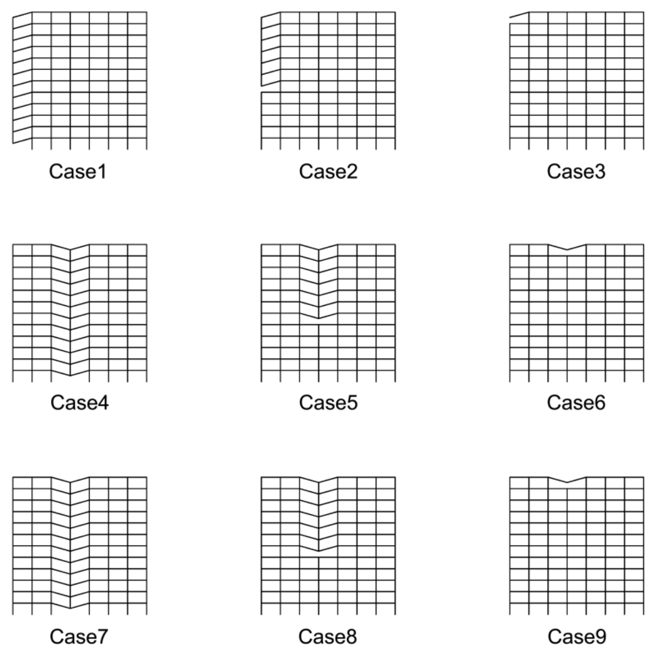

Figure 6 schematic progressive collapse procedures for cases 1 to 9

6. RESULTS AND DISCUSSION

Due to the elimination of a column, some plastic joints are created which are usually formed in the beams [14]. The result of dynamic analysis of the structure indicates that after re-strengthening and re-analyzing, the plastic joint was not formed in the intended structure. This means that the member behaviour had remained linear and hadn't entered the plastic zone. For a precise comparison according to the defined scenarios, the different columns were eliminated and the displacements of the upper nodes were studied. In Figures 6 to 14 the system response to the sudden elimination of the column has been shown. As can be seen in all 9 defined scenarios, the displacements of the system has been done from the second 0 to t_1=5^{sec} in a linear fashion with a moderate slope

illustrating the consistent applied loads to the system. Obviously the declining slope in the graph between 0 and 5^{sec} are as a result of the existence of braces. From $t_1=5^{sec}$ to $t_2=7^{sec}$ according to the applied loads time history function in the Figure3, there is no accidental change in the system. However, the displacements in all positions are constant and invariant. In the moment $t_2=7^{sec}$ as soon as there is an accidental fault in the system and the column elimination, an alternate accidental displacements happens. From $t_2=7^{sec}$ to $t_3=10^{sec}$, the system after an alternate vibration becomes mortal in a specific displacement.

According to Figure6, Figure 7 and Figure 8, the function of case1, 2 and 3 show that with the elimination of the column on the first floor, the displacements of the upper node of the eliminated column formed after the fault in the system accidentally reached from 4.1^{mm} to 89.8^{mm} and finally after an alternation becomes mortal to 58.4^{mm}. Also, with the column elimination on the 6th floor, the displacement had changed from 5.3^{mm} to 109.7^{mm} and was stabilized at 73.1^{mm}. With the elimination of the same column from the last floor the displacement had reached from 6.1^{mm} to 138.3^{mm} and finally got mortal at 85.3^{mm}. Needless to say, with the column elimination at upper floors, the range of accidental changes of displacement of the upper point of the eliminated column increased.

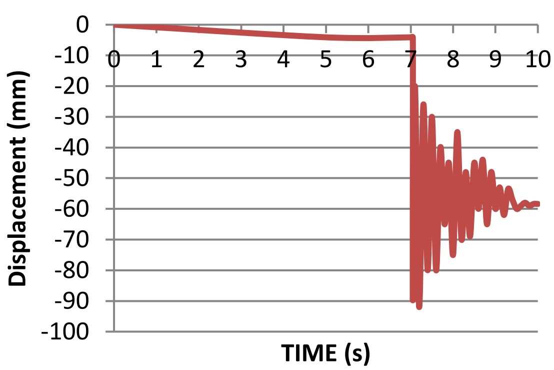

Figure 7 Displacement time history of case 1

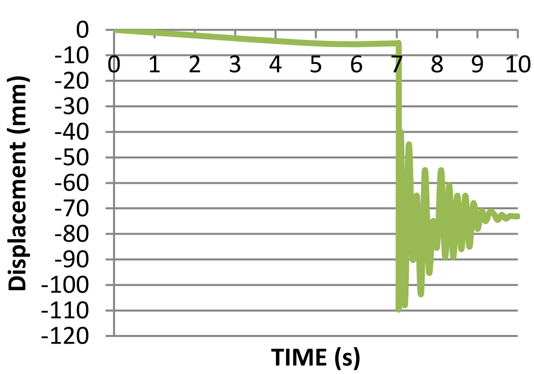

Figure 8 Displacement time history of case 2

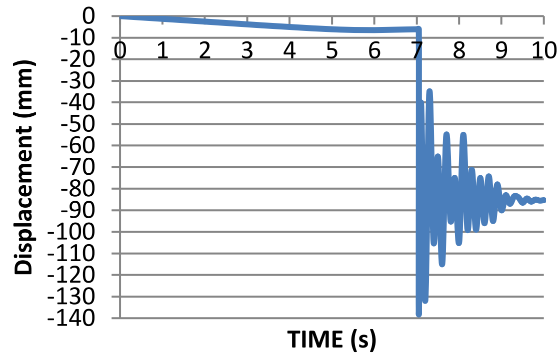

Figure 9 Displacement time history of case 3

Figures 9 to 11 shows the displacement graphs based on time in cases 4 to 6. In these cases, the displacements of the upper points of the column after elimination of the side column have been illustrated. In case4, when the eliminated column is the side column on the first floor, the amount of the displacement changed from 3.9^{mm} to 81.2^{mm} and got mortal at 53.6^{mm}. Interestingly, with the elimination of the side column and also increasing the floors, the amount of displacements increased in a way that in case5 with the elimination of the column on the 6th floor and case 6 that is column elimination on the last floor, the amount of its displacements reached from 4.9^{mm} to 101.4^{mm}, and from 5.4^{mm} to 123.9^{mm} respectively and got mortal at 64.9^{mm} and 78.1^{mm}.

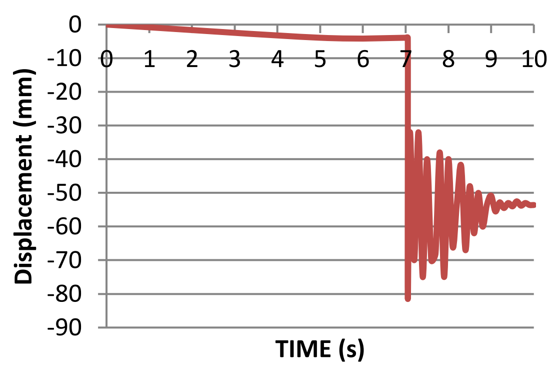

Figure 10 Displacement time history of case 4

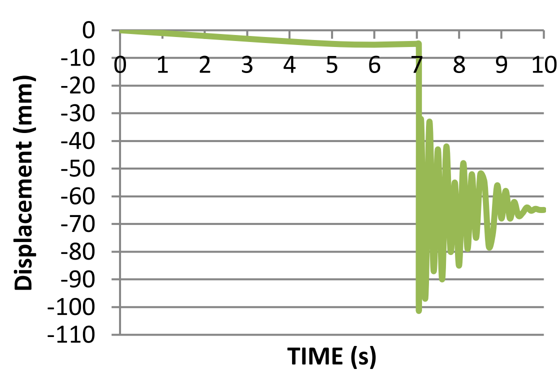

Figure 11 Displacement time history of case 5

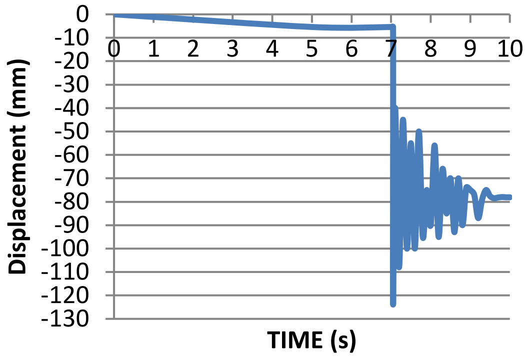

Figure 12 Displacement time history of case 6

Doing a dynamic analysis for the middle column elimination in different positions in Figure12, Figure13 and Figure14, it can be seen that with the column elimination on the first floor in case7 the upper point displacement of the column reached from 3.3^{mm} to 69.3^{mm} and stabilized at 46.5^{mm}. The displacement of the upper point of the column if eliminated on floor 6 also in case8 reached from 3.8^{mm} to 89.0^{mm} and got mortal at 59.4^{mm}. Moreover, in case of column elimination in the last floor, displacement changed reached from 4.7^{mm} to 110.6^{mm} and after an alternation reached the final amount of 70.8^{mm}.

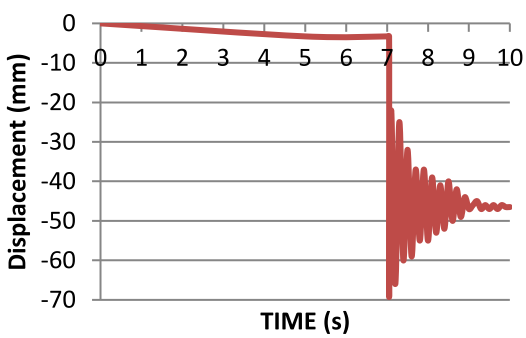

Figure 13 Displacement time history of case 7

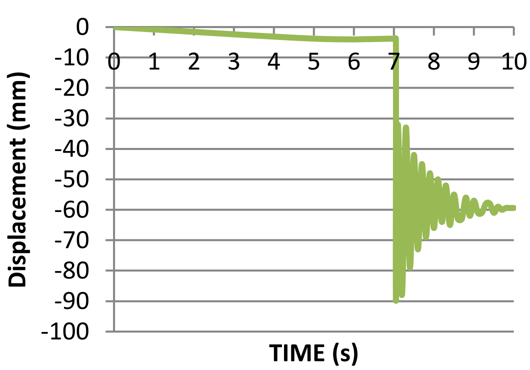

Figure 14 Displacement time history of case 8

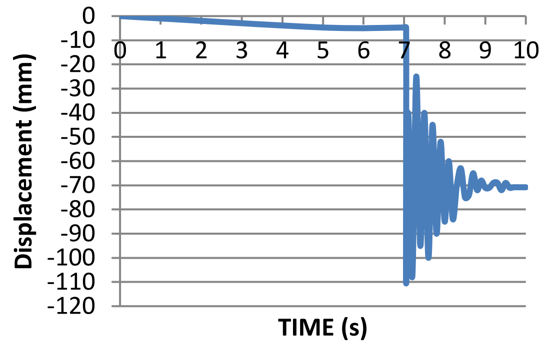

Figure 15 Displacement time history of case 9

Examining the results indicates that with the increase in the floors, the displacements in the upper point of the column also increase. Furthermore, moving away from the middle columns to the side columns and from the side columns to the corner columns, one can observe increase in the displacement of the points. This means that the corner columns are more vulnerable than the side and middle columns against the progressive collapse potential. In conclusion, the middle columns show more resistance against this fault. This can happen as a result of the more number of connected members to the disabled member and subsequently redistribution in the inner force in more members.

7. CONCLUSION

The progressive collapse is a chain-like destruction caused by unpredictable abnormal loads in design such as accidents and explosion during which the destruction of a structural element disseminating to other members could cause the destruction of one or more parts of the structure. This phenomenon in vital buildings of the city like hospitals, power plants, etc., which must be on the immediate occupancy servicing list could be perilous. To meet this end, in this study, a 12 stories building with the eccentric braced frame according to the design codes of Iran was modeled and designed and using the APM method explained in DoD and GSA guidelines, eliminating columns based on defined scenarios, the system response to the column destruction was studied. Based on DoD2009 guideline suggestions, the column elimination in the first, middle, and last floors in the side, middle, and corner columns for the structure were investigated and the displacements of the upper point of each column in all positions was studied. The results of the dynamic analysis show that:

a) The eccentric braced frame system has passed the progressive collapse with long displacements and didn't enter the plastic area. So it can be said that this system has good energy absorbing.

b) The location of the eliminated column in the plan is so effective in dissemination of the progressive collapse that moving from the corner columns to the side columns and from the side columns to the middle ones this destruction decreases.

c) The number of the floor whose column was eliminated due to whatever reason is so effective in dissemination of the progressive collapse that the more we move to from the lower floors to the upper ones, the more displacements we see. So it can be said that with the column elimination in the lower floors the dissemination of the destruction happens in vertical and floor ways while with the column elimination in upper floors the dissemination of destruction would happen horizontally.

According to the above results it is suggested that for structures with high importance, the dynamic analysis potential of the progressive collapse using the APM method be taken into account.

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